Thermal Protection and Fire Resistance of High-Pressure Hydrogen Storage

Makarov, D.*[1], Kim, Y.[2], Kashkarov, S.[1], Molkov, V.[1]

[1] *Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, Shore Road, Newtownabbey, BT37 0QB, UK*
[2] *Korea Institute of Civil Engineering and Building Technology, 283 Goyangdae-ro, Ilsanseo-gu, Goyang-si, Gyeonggi-do, 10223 Republic of Korea*
**Corresponding author email: dv.makarov@ulster.ac.uk*

ABSTRACT

The paper focuses on the main unresolved safety issue for hydrogen-powered vehicles, i.e. the fire resistance of onboard hydrogen storage. The experimental study supported by numerical analysis has been undertaken in order to achieve fire resistance rating of high-pressure hydrogen tank beyond potential car fire duration, i.e. of the order of 2 hours. The experimental programme comprised of bonfire tests of carbon-fibre reinforced plastic tanks with polymer liner both bare and thermally protected, in line with Global Technical Regulation on Hydrogen and Fuel Cell Vehicles #13. Tested parameters included different levels of thermal protection, different bonfire heat release rates, tanks with and without prehistory of pressure cycling. It was experimentally demonstrated that the thermal protection solution in form of epoxy-based intumescent paint is capable to increase fire resistance rating of carbon-fibre plastic tank from current 6-12 minutes to beyond 2 hours. This breakthrough achievement in fire resistance rating of onboard hydrogen storage has a potential to impact on safety design of tanks and to reduce range of hazards in case of accident scenario like a car fire, e.g. complete elimination of catastrophic tank rapture in a fire or longer release from a pressure relief device resulting in a shorter hydrogen jet fire. Smaller bonfire heat release rate was shown to increase fire resistance rating of the tested tank though still complying with the Global Technical Regulation #13. Tank pressure cycling did not have impact on the tank fire resistance rating.

KEYWORDS: Hydrogen, high-pressure tank, bonfire, fire resistance, thermal protection, safety.

INTRODUCTION

Hydrogen powered vehicles are already commercially available and in the public domain. The fire protection of onboard high-pressure hydrogen storage is one of the most urgent unresolved technological issues. Achieving comparable with conventional cars driving range requires hydrogen storage pressures up to 700 bar, which in turn dictates use of Type 4 high-pressure tanks made of carbon-fibre reinforced polymer (CFRP) with plastic liner. Previous experimental studies [1-3] indicate that fire resistance of bare unprotected Type 4 tanks is of the order 6-12 minutes. This is very short time compare to a car fire duration, which can be as long as 1 hour 40 minutes according to the recent review of the car fire research [6]. With more than 23,000 car fires happened in UK in 2013-2014 [4], and more than 193,000 car fires in USA in 2014 [5], fuel cell vehicle fire is a realistic scenario to which industry and rescue services should be prepared.

Current regulations, codes and standards (RCS) require a tank to be equipped with temperature activated pressure relieve device (TPRD) to prevent its catastrophic failure in fire. Thus, Global Technical Regulation on Hydrogen and Fuel Cell Vehicles (GTR#13) [7] specifies “Test procedures for service terminating performance in fire” and set conditions for localised and engulfing fire tests. However, there is no requirements to fire resistance rating (FRR) of the tank and the only safety requirement to operation of TPRD is that “the container shall vent through a

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pressure relief device without bursting" [7], i.e. the tank should vent before rapture. Resulting hydrogen jet fire poses a substantial hazard to public, passengers and first responders due to its large heat release rate (HRR) and long jet flame. Furthermore, GTR#13 introduces both localised and engulfing bonfires as qualification tests: fire scenarios are prescribed as a temperature history, not in terms of heat flux on the tank surface, which occurs in a realistic car fire. This may be a source of discrepancies when bonfire tests are conducted using different testing facilities and different burners.

Fire protection of composite tanks was addressed previously, though was aimed at prevention of tank rapture in a localised fire. Gambone and Wong [8] performed experiments testing different fire protection techniques including ceramic insulating material sprayed over a composite tank, ceramic fire blanket and use of a fuel system encapsulated into a fire resistant foam. Similarly, Webster [9] tested fire protection of composite tanks using an intumescent system in a water resistant polymer latex, intumescent epoxy coating, and various ceramic fibre blankets. However, in both studies the aim of research was not to improve safety associated with hydrogen blowdown through TPRD and not to avoid completely a catastrophic tank rapture, but to sustain tank in a fire until the moment when fire grows enough to reach and trigger TPRD. As a result, the maximum duration of bonfire experiments in [8] was 45 minutes and in [9] – just 30 minutes.

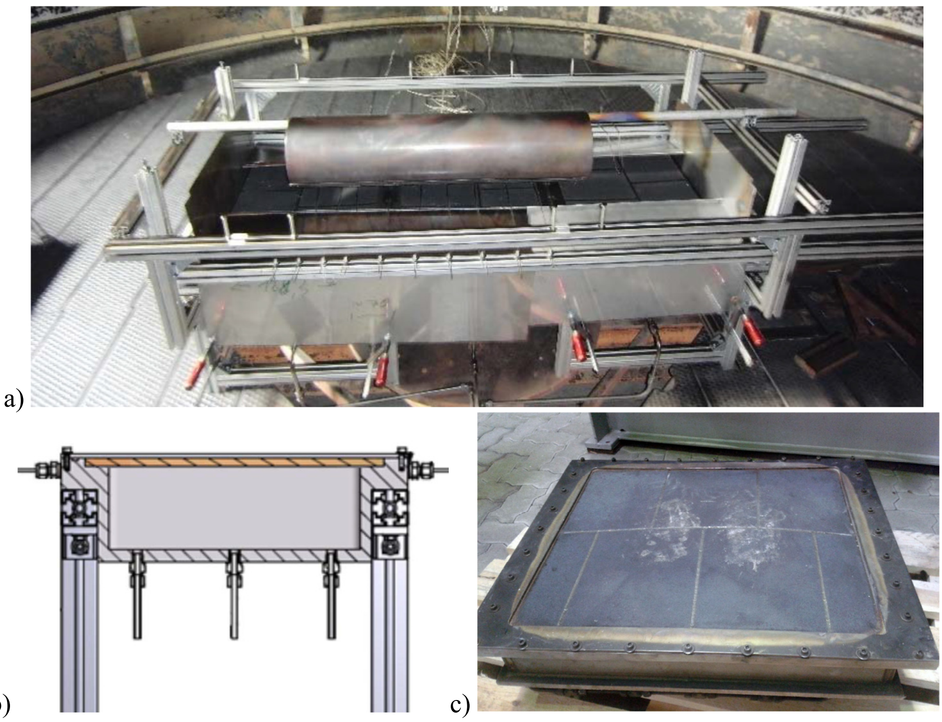
The aim of the reported below experimental study was to achieve a breakthrough FRR beyond potential car fire duration, i.e. of the order of 2 hours. Longer fire resistance would allow slower hydrogen release from TPRD, shorter hydrogen jet fire, safer intervention by first responders and evacuation, inherently safer public environment. Achieving fire resistance beyond 2 hours would help to avoid a catastrophic tank rapture even in the case of complete TPRD failure.

EXPERIMENTAL FACILITY

Bonfire tests were performed at Karlsruhe Institute of Technology (KIT) (Germany) installation HyKA-A2 in the framework of European FCH-JU project H2FC (www.h2fc.eu), see Figure 1. The facility is comprised of a sealed vessel with diameter 6.0 m and height 9.0 m, empty vessel volume 220 m^3. The vessel was designed for explosion tests with static overpressure up to 10 atm. The vessel is thermo-insulated, may be heated up to 150^{o}C, and may be filled with inert atmosphere. Access to the vessel is through three 2.0 m diameter hatches. The instrumentation which may be deployed includes thermocouple array, piezoelectric and piezoresistive gauges (initial pressure, explosion pressure), gas analyser and mass spectrometer (to control mixture composition), sonic hydrogen sensors, etc. The data acquisition system is based on multi-channel (64) ADC with a sampling rate of 1 MHz.

To avoid hydrogen combustion after tank rapture the experiments were run in nitrogen atmosphere when tank was filled with hydrogen or in air atmosphere when tanks were filled with helium. To conduct bonfire test in inert atmosphere the facility was equipped with premixed methane-air burner. The burner was made of three sintered metal plates having sizes 0.570 m × 0.497 m and installed on top of a mixing chamber. The total burner dimensions were 1.745 m × 0.7 m, which is in line with GTR#13 requirements. The facility is equipped with gas supply system allowing maximum HRR of methane-air combustion about 170 kW. To better heat the tested sample the burner had so called "guide plates" directing hot combustion products to the tested sample. Figure 2(a) gives a general view of the burner with a dummy cylinder mimicking high-pressure tank (no "guide plates"). Schematic view of the burner and its mixing chamber is given in Figure 2(b), and sintered metal plate is shown in Figure 2(c).

Figure 1. HYKA-A2 facility at KIT.



a) b) c)

Figure 2. a) Methane-air burner with a dummy cylinder (no "guide plates"), b) scheme of the burner mixing chamber, c) sintered metal plate.

NUMERICAL PRETEST PROGRAMME

Simulation programme was conducted prior to experimental trials aiming to guide experiments and to test potential to achieve a breakthrough FRR. At first stage a bare unprotected tank mounted on the KIT facility burner was modelled and bonfire test similar to the one expected in KIT facility was simulated using computational fluid dynamics (CFD) technique. The model employed three-dimensional incompressible problem formulation, k-ε turbulence model with standard wall functions [10] and Eddy Break-Up combustion model [11]. The heat flux on the central section of the tank surface as a function of tank surface temperature was obtained in simulations. At the next step a one-dimensional model of tank protected by intumescent paint was developed and simulations were run using previously obtained heat flux as a boundary condition.

Simulation of tank rapture requires a model for loss of load bearing ability of the tank. The assumption that the local load-bearing ability of carbon-fibre plies is lost on reaching the glass transition temperature of composite resin was adopted as a first approach. From the GTR#13 requirement for the tank burst pressure to be 2.25 times higher than its normal working pressure it was further assumed that the fraction of tank wall thickness, still sufficient to carry its normal working pressure load 70 MPa, was 1/2.25=0.44. Thus, the total criterion worked as follows: the tank load bearing ability is supposed to be lost when temperature wave equal to the glass transition temperature was passing through 0.56 fraction of the tank wall thickness. The model was realised using ANSYS Fluent as CFD platform and more model and simulation details are available in [12].

Figure 3 shows simulated FRR of bare and protected by intumescent paint tank as a function of resin glass transition temperature for three different intumescent paint thicknesses – 10.0, 13.5, and 16.5 mm; the figure also shows fire resistance rating of bare unprotected tank for three different HRR – 78, 168 and 370 kW (though the last one is hypothetical for the considered KIT installation).

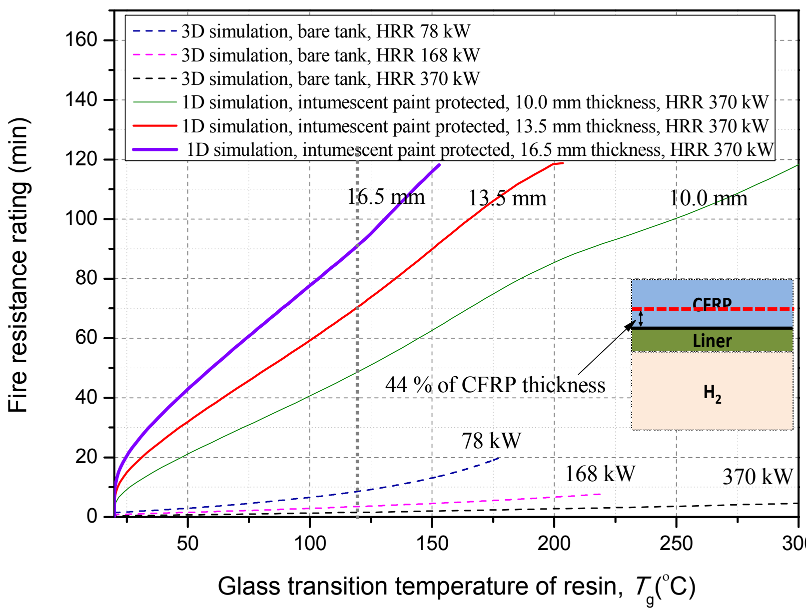


Figure 3. Simulated FRR of the tank as a function of the composite resin glass transition temperature.

Pretest CFD simulation results in Figure 3 clearly show that the intumescent paint protection is capable to deliver an order of magnitude longer FRR. Indeed, simulated FRR of bare unprotected tank with glass transition temperature T_g=120°C when exposed to 370 kW fire is just about 2 minutes, while for the same tank, but protected by 16.5 mm intumescent coating, FRR is about 90 minutes.
Another important result of pre-test CFD simulations is dependence of FRR on bonfire HRR. Though all three simulated bare tank tests complied with GTR#13 requirements in terms of temperature profile (i.e. temperature 25 mm below tank attained value above 590°C within 5 minutes after fire is ignited), the resultant FRR is quite different.

EXPERIMENTAL RESEARCH SUMMARY AND DISCUSSION

Experimental programme

The tested Type 4 tanks had internal volume 36 litres, length 0.910 m, diameter 0.325 m. Totally 6 high-pressure hydrogen storage tanks were tested, see experimental programme matrix and results in Table 1. The tested variable parameters included

- level of thermal protection - bare unprotected tank, tanks with epoxy-based intumescent paint (20 mm and 7 mm thickness), tank protected by metal shell and thermo-insulating filler (isofrax),
- aging effect – tank without testing prehistory ("virgin"), and tank after pressure cycling testing ("aged"),
- effect of bonfire HRR - experiments with two different HRRs (79 kW and 170 kW) were performed to confirm experimentally the discovered in CFD simulations dependence of FRR on bonfire heat release rate.

There were no TPRDs installed on the tanks as the research aimed to study tanks' FRR. For this reason no difference was expected between localised and engulfing fires, and the testing procedure of GTR#13 for engulfing bonfire test was employed. A commercially available epoxy-based intumescent paint was used in the described research.

Table 1. Summary of experimental programme and results.

Test	Tank prehistory	Heat release	Tank thermal protection	Atmosphere	Filling gas	Failure time
1	New	170 kW	-	N_2	H_2	8 m 04 s
2	Aged	170 kW	-	N_2	H_2	9 m
3	Aged	79 kW	-	N_2	H_2	16 m 23 s
4	Aged	170 kW	Intumescent paint, 7 mm	Air	He	1 h 05 m
5	Aged	170 kW	Intumescent paint, 20 mm	Air	He	1 h 51 m 35 s (test stopped)
6	Aged	170 kW	Metal shell protection	Air	He	1 h 11 m

Tank aging

Majority of tanks provided for bonfire testing had pressure cycling prehistory. To study effect of tank prehistory on its FRR two tests were conducted to compare performance of a new ("virgin") tank and a tank with prehistory ("aged"). New tank burst catastrophically after 8 minutes and the aged tank - after 9 minutes in bonfire. This FRR is in line with previous experimental studies [1-3]. The fact that the aged tank failed later than the new one suggests that 1) the aging does not have effect on the FRR of the tank, 2) the difference in results is due to the experimental scatter.

Both small scatter of new and aged tanks' FRR (with identical bonfire HRR) and similarity of the obtained results to the data available in the literature [1-3] confirms validity of testing procedure.

Bonfire HRR

Discovered in pretest CFD simulations effect of bonfire HRR on tank FRR was tested experimentally. Bare unprotected tank was tested in a bonfire with HRR 79 kW (Test 3) and provided FRR 16 minutes and 23 seconds. It is twice longer than FRR for the new tank with HRR 170 kW in Test 1 and 1.8 times longer than the same in Test 2, proving that the bonfire HRR does affect composite Type 4 tank FRR.

Figure 4 shows temperature profiles measured by three thermocouples installed 25 mm below tank surface. The Figure demonstrates that the GTR#13 requirement for engulfing test fire to achieve average between 2 thermocouples temperature 590°C within 5 minutes from fire ignition was satisfied for both Test 1 (170kW) and Test 3 (79 kW), though maximum temperatures were different between two tests resulting in different FRR.

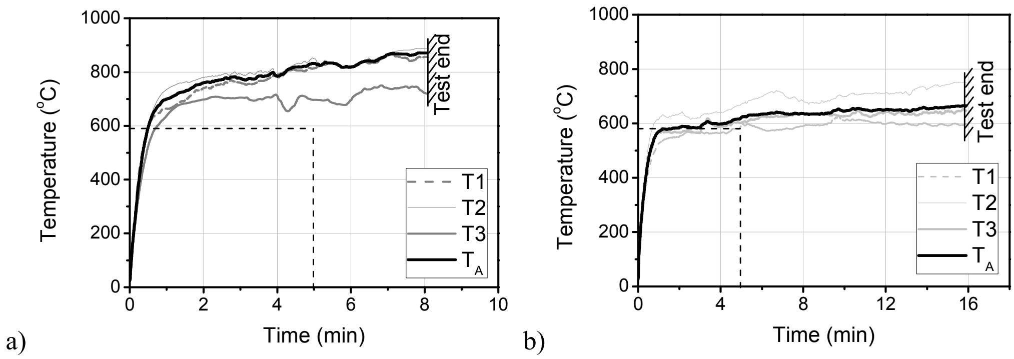


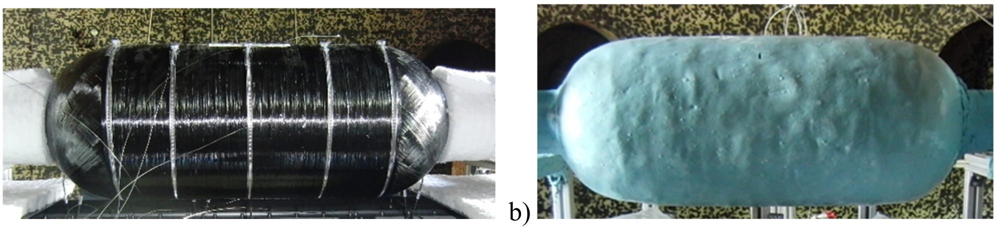
Figure 4. Temperature profile in three thermocouples installed 25 mm below tank surface: a) Test 1 (170 kW), b) Test 3 (79 kW).

Thermal protection

Tanks protected by intumescent paint coatings 7 mm (Test 4) and 20 mm (Test 5), and tank protected by metal shell with thermo-insulation filler (Test 6) were tested and effect of thermal protection on increase of FRR was studied in comparison with result for bare unprotected tanks (Tests 1 and 2). Bare unprotected and 20 mm intumescent paint coated tanks before experiment are shown in Figure 5.

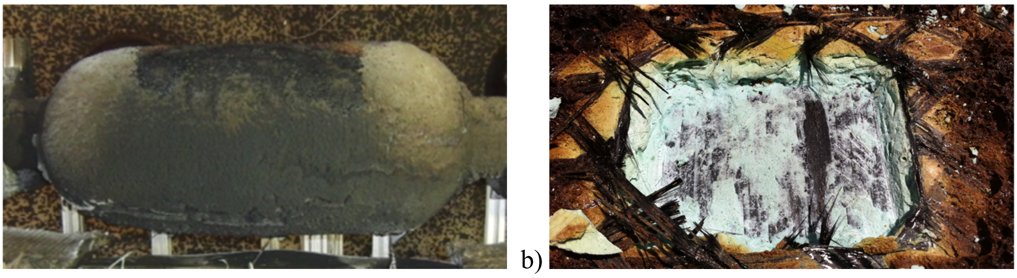
The best (i.e. longest) FRR was obtained for the tank protected by 20 mm intumescent coating – the test had to be stopped after 1 hour and 51 minutes duration due to the shortage of fuel for methane-air burner. The tank retained integrity and did not leak hydrogen. Close inspection of the tank revealed that only a part of the intumescent coating reacted and some intumescent material remained intact indicating potential for even longer FRR should the bonfire test continue further. General view of the 20 mm coated tank after the test and cut through the intumescent coating is shown in Figure 6. The obtained in Test 5 FRR represents a breakthrough for onboard high-pressure hydrogen storage safety achieving tank protection beyond duration of the longest possible vehicle fire. The fact has a potential to impact drastically on public safety, life and property protection, and intervention strategy of first responders when dealing with fuel cell vehicles.

The tank protected with 7 mm thick intumescent paint coating failed after 1 hour and 5 minutes of bonfire and fire resistance rating of tank protected using metal shell with thermo-insulating filler between the tank and the shell (shown in Figure 7) was 1 hour 11 minutes. Though these are shorter time durations than in the case of 20 mm coating, it is still a spectacular improvement compare to a bare unprotected tank performance in bonfire, especially taking into account the relatively low cost of intumescent paint fire protection solution.



a) b)

Figure 5. Tanks before tests: a) bare unprotected tank, b) 20 mm intumescent paint coated tank.



a) b)

Figure 6. 20 mm coated tank after the test: a) general view, b) unreacted intumescent paint in the cut through the charred paint layer.

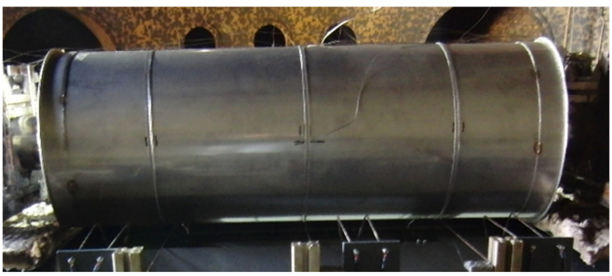


Figure 7. General view of metal shell protected tank installed for bonfire test.

CONCLUSIONS

Fire resistance of current composite tanks in bonfire is of the order 6-12 minutes, dictating requirement to vent hydrogen tank before its rapture creating a violent jet fire and compromising public and first responders' safety. The described research aimed to improve fire safety of fuel cell vehicles by increasing fire resistance rating of oboard hydrogen storage and allowing safe evacuation of passengers, intervention of emergency services and improved public safety.

Combined numerical and experimental study demonstrated that fire resistance rating of composite Type 4 high-pressure tank may be relatively easy increased beyond the longest recorded car fire duration 1 hour 40 minutes. Numerical research suggested that a breakthrough in Type 4 tank fire resistance may be achieved using intumescent paint protection, and at least 1 hour 51 minutes fire resistance rating was demonstrated experimentally with 20 mm thick epoxy-based intumescent paint coating.

Dependence of fire resistance rating on bonfire heat release rate was predicted in CFD simulations and confirmed experimentally. This highlights a knowledge gap in bonfire protocol specification in current regulations – no data available on realistic heat fluxes to which onboard high-pressure tanks are exposed in a car fire.

No effect of tank aging (i.e. pressure cycling) on its fire resistance rating was observed in the performed experiments.

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